AFOSR-TR-72-2029

FINAL SCIENTIFIC REPORT

INTERFACE PHENOMENA IN ENGINEERING MATERIALS

by

Edwin J. Scheibner

This research was supported by the Air Force
Office of Scientific Research (AFSC) under
Contract F44620-68-C-0008 (Project THEMIS)

Georgia Institute of Technology
Atlanta, Georgia 30332

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I. ABSTRACT

The purpose of the research studies under Project THEMIS (Contract F44620-68-C-0008) was to examine in a fundamental manner various phenomena occurring at interfaces between different materials or between different phases of the same material, including the gas-solid interface. Of particular importance was the fact that these studies were to be directed towards an understanding of the influence of interfacial conditions on the behavior of materials in engineering applications. A multi-task, multi-discipline effort provided a broad research program which included: fundamental surface science, e.g., adsorption and surface thermodynamics; the development of surface analytical techniques, e.g., improved Auger electron spectroscopy and micromechanical techniques; engineering applications, e.g., friction and wear, and semiconductor process studies; and detailed investigations of fabrication methods, e.g., chemical vapor deposition and sintering.

Project THEMIS was a program of the Department of Defense having two specific objectives: 1) the development of basic knowledge at new centers of excellence for use in solving future defense problems; and 2) the strengthening of the graduate program of educational institutions. The material summarized in this report indicates how these objectives were achieved at the Georgia Institute of Technology.

II. SUMMARY OF RESEARCH

1. Introduction and Research Goals

Many engineering materials which have desirable structural properties unfortunately are also highly susceptible to environmental factors such as chemical attack in a gaseous or liquid medium. In military applications of certain of these materials, normal stresses combined with the environmental factors can cause catastrophic failure of a critical structural member. Other materials are used in device applications where physical, metallurgical, and chemical phenomena at interfaces play a vital role in performance and reliability. The research performed under Project THEMIS (Contract F44620-68-C-0008) was directed towards a fundamental understanding of these and other problems related to the influence of interfacial conditions on the behavior of engineering materials.

Project THEMIS was initiated by the Department of Defense (DoD) in 1967 as a national program designed to develop new centers of excellence capable of contributing basic knowledge for use in solving future defense problems. Its concept provided for program-oriented research in which it was possible to achieve at a single institution a coordinated multi-task, multi-discipline team effort directed towards a specific area of science or engineering. Consistent with this objective was the recognition that the program should contribute to the strengthening of the graduate program in accordance with the long range educational goals of the institution. Another objective of THEMIS was the establishment of closer relationships between university scientists or engineers and the DoD laboratory scientists and engineers who are regularly concerned with the analysis of long-term military problems and missions.

The Department of Defense had identified eight relevant research areas suitable for THEMIS support; one of these was materials science and engineering. At Georgia Tech we recognized the importance of interface phenomena in a number of practical problems in the materials area and therefore proposed on 1 May 1967 to establish an interdisciplinary research program on "Interface Phenomena in Engineering Materials," building upon our existing strengths and interests.

The research studies under our THEMIS program were initiated on 1 September 1967 and were continued until 31 August 1972 with a reduced effort during the last two years. Twelve independent but related tasks comprised the total research effort. Titles of these tasks, the task leaders, and a statement of the research goals are as follows:

Thermodynamics of Interfaces (J.C. Eriksson)

To develop, from previous studies on the thermodynamics of surface phases in fluid systems, a general thermodynamic theory to include both physical adsorption and chemisorption.

Measurement of Thermodynamic Quantities (B.R. Livesay)

To measure the surface tension of solid interfaces and the changes in it that may be due to the adsorption of various gases.

Electron Interactions With Solids (L.N. Tharp)

To develop means of characterizing solid surfaces with respect to structure and composition for sub-monolayer coverages of impurities.

LEED Studies of Gas-Solid Interactions (G.W. Simmons)

To study gas-solid interactions for specific chemical systems of interest to other tasks in the program, by low energy electron diffraction (LEED) and related techniques.

Optical Studies of Interfaces in Controlled Environments (J.R. Stevenson)

To characterize the dielectric properties of an interface region experimentally by investigating the complex index of refraction in a frequency interval (near infrared into vacuum ultraviolet) where the interface is highly absorbing.

Field Emission and Field-Ion Microscopy (R.F. Hochman and H.E. Grenga)

To apply field emission and field-ion microscopy to the study of the structure and surface characteristics of solid surfaces and interfaces of engineering materials.

Ultrasonic Effects on Metal Processing: Surface Tension (R.F. Hochman)

To determine the effect of ultrasonic energy on the surface energy of solids and on the solid-liquid interface during solidification.

Adhesion, Friction and Wear Studies (M.E. Sikorski)

To investigate those fundamental properties of materials which influence adhesion, friction and wear phenomena.

Machinability of Metals (J.A. Bailey)

To study the forces at the chip-tool interface during machining operations and the effects of lubricants containing chlorine, bromine, iodine or fluorine on the reduction of frictional forces.

Solidification of Metals (J.A. Murphy)

To study the conditions at the liquid-solid interface during the casting of metals into metal molds.

Gas-Solid Interactions (R.A. Pierotti)

To obtain high and low temperature data for the interaction of non-reactive gases with graphite and boron nitride and then to analyze these data in terms of statistical thermodynamics models to elucidate the nature and magnitude of the forces acting between the gas and the solid, and among gas molecules in the presence of the solid.

Surface and Diffusion Coatings (C.W. Gorton)

To identify technology gaps and specific research problems related to surface and diffusion coatings and to undertake a parametric experimental study for the preparation of a particular coating using chemical vapor deposition.

2. Review of Achievements

In this section the research performed under the various tasks of the program is briefly reviewed, changes in emphasis are mentioned, and appropriate references in the published literature are noted.

a) Thermodynamics of Interfaces

In previous studies[1-4] of the thermodynamics of plane surface phase systems, Eriksson stressed the importance of a surface phase of non-zero thickness. Thermodynamic components could have, in this region, values that may be considerably different from their bulk values. This approach is more realistic than the use of the Gibbs "dividing surface" where such "surface excesses" are located, in earlier formulations of surface thermodynamics. The systems considered previously by Eriksson were fluid surface phase systems. In this research the general thermodynamic concepts were extended to the solid-gas interface.[5] In the paper a fundamental equation is derived for the surface phase of a solid exposed to an adsorbing gas and measurements of dimensional changes upon adsorption, heats of adsorption and surface structure transitions are discussed on the basis of the formalism.

b) Measurement of Thermodynamic Quantities

The macroscopic quantity of particular importance in the thermodynamics of surface phases is the surface tension, γ. While this quantity can readily be determined for fluid surface systems, for solid surfaces there are relatively few experimental studies, except for metals close to the melting point. Several investigators, however, have studied dimensional changes of porous solids which occur at gas adsorption.[6] These studies are discussed by Eriksson.[5] Porous solids have surfaces which are relatively undefined with respect to structure and composition and, therefore, fundamental information on surface tension and localized adsorption is difficult to extract from the results. On the other hand the surfaces of thin foil samples can be cleaned and characterized. When subjected to a constant stress such samples will experience a change in the state of strain if the surface tension is altered by gas adsorption. Measurements of the dimensional changes by optical lever or interferometer techniques should be made as a function of gas pressure and sample temperature. In this research task equipment was designed and constructed for performing such measurements.

Before undertaking studies of dimensional changes on gas adsorption it was considered essential that studies be made of the mechanical properties, i.e., stress vs strain, of thin foils and the effects of changing interfacial energies by depositing various films on the foil samples. Techniques were developed for preparing thin single crystal tensile specimens and for measuring their mechanical properties. In his doctoral dissertation B. R. Livesay[7] interpreted the results in terms of dislocation interactions with the interface. Research under this task was continued by B. R. Livesay and E. A. Starke, Jr. under Air Force Grant No. AFOSR-71-2064 on "Effects of Interface Phenomena on Mechanical Behavior of Metals."

c) Electron Interactions with Solids

Under this task several improvements were made in the experimental techniques for using Auger electron spectroscopy in the characterization of surfaces. For example, one experimental system assembled consisted of a large bell-jar type ultra-high vacuum system equipped with a turbomolecular pump-ion pump combination, a spherical retarding field electron energy analyzer for generating the Auger spectra and a special multiple sample turret assembly for sequentially analyzing several samples inserted at the same time. This system was particularly useful in studies[8] of semiconductor device processing (supported by NASA under Contract No. NAS 8-25667) and in studies of quartz crystal resonators.[9]

Another study of Auger spectroscopy applied to semiconductor surface problems is being completed by R. P. Woodward for a Ph.D. dissertation in the School of Electrical Engineering. Improvements in this work include the use of a high current density electron gun, the analysis of sample current to determine optimum conditions for avoiding charging and other artifacts that confuse the interpretation of Auger spectra, and the calibration of Auger electron intensities for different angles of incidence of the primary electron beam. This work also elucidates the mechanisms of carbon contamination and removal on silicon and silicon dioxide surfaces.

d) LEED Studies of Gas-Solid Interactions

A general purpose gas-solid reaction chamber was built into a conventional ultra-high vacuum LEED system for studying materials in highly corrosive atmospheres under a wide range of pressures and temperatures. In initial investigations with this system low energy electron diffraction (LEED) was used to study the surface structures of titanium single crystals that accompany reactions at the solid-gas interface and Auger electron spectroscopy was used to identify the elemental composition of the surfaces studied. Order-disorder phenomena at the surface of α-titanium-oxygen solid solutions was observed for various oxygen pressures and correlated with published experimental data on bulk specimens.[10] Because of the difficulties encountered in keeping the titanium samples oxygen free during preparation of the surfaces an apparatus was constructed for depositing thin films in situ. Studies were then made of aluminum, titanium, vanadium and chromium films by Auger electron spectroscopy and by the analysis of characteristic energy losses in the inelastic electron spectrum.[11,12] (The titanium work was partially supported by the Advanced Research Projects Agency under Contract No. Nonr-991(15) with the Naval Research Laboratory).

The 3d transition metals were also studied theoretically by Phillips[13] who investigated the LMM Auger transition probabilities and energies in titanium, vanadium, chromium, zirconium, niobium and molybdenum.

e) Optical Studies of Interfaces in Controlled Environments

The dielectric properties of a material are usually characterized by a frequency-dependent response function in the form of a complex dielectric constant, a complex conductivity, or a complex index of refraction. The frequency interval in which a dielectric response function is changing rapidly is indicative of an absorption process taking place in the material. Whenever the absorption is very strong, the high attenuation of the electromagnetic disturbance makes the reflected radiation characteristic of the dielectric properties of the interface between the transparent incident medium and the highly absorbing reflecting medium.

In the research of this task optical reflectivity studies were made of the semiconductor alloy system $Cd_x Zn_{3-x} As_2$ in the frequency interval from the near infrared into the vacuum ultraviolet. The semiconductor specimens were obtained from the Semiconductors Branch of the U.S. Naval Research Laboratory where theoretical calculations of band structure were being performed. The vacuum ultraviolet reflectivity data[14] were obtained at the University of Wisconsin using the synchrotron radiation from the storage ring. Samples were maintained in an ultra high vacuum chamber and Auger spectroscopy was used to analyze the extent of surface contamination.[15]

Research under this task was continued under Air Force Grant No. AFOSR-70-1892.

f) Field Emission and Field-Ion Microscopy

Initially the work under this task involved the development of techniques for examining the various types of interfaces occurring in eingineering alloys, i.e., grain boundaries, G.P. zones, two phase boundaries, order-disorder anti-phase boundaries, etc. Field ion microscopy studies of ordered Ni_4Mo and the fine structure in alloy steels were made.[16,17] Titanium and Ti_3Al were also examined although it was difficult to image these materials.[18]

Research under this task was continued under NSF Grant GK-26487.

g) Ultrasonic Effects on Metal Processing: Surface Tension

Preliminary experiments were made during the first year on the surface tension of mercury on aluminum. Using the sessile drop technique a measurable decrease in surface tension was observed when the aluminum plate was ultrasonically activated. While the effects of ultrasonic excitation could have important consequences in problems involving solid-liquid interfaces, e.g. solidification, we were unable to provide sufficient concentration of effort to obtain definitive results. The research under this task was therefore discontinued.

h) Adhesion, Friction and Wear Studies

A twist compression bonding technique[19] was used to determine the coefficient of adhesion in air for alloys of a variety of compositions from the solid-solution systems Cu-Au, Cu-Ni, Au-Ag, Ag-Pd and Pt-Co. It was shown[20] that the coefficient of adhesion depends on chemical composition as well as by changes in the crystal structure produced by atomic ordering.

When the twist compression technique in air is used to investigate the adhesion of hard metals (Knoop hardness greater than about 400), it is found that the adhesion coefficients are rather small. An apparatus was constructed for performing twist compression studies under ultra high vacuum conditions and results were obtained for an ordered platinum-cobalt alloy.[21] Using the same apparatus a study was made of the adhesion between high purity copper specimens in vacuum and compared with measurements in air.[22]

A simple modification within the ultra-high vacuum system used for adhesion studies allowed a study to be made of the initial stage of vacuum sintering of pure metals, considered to be a high-temperature creep process.[23]

Finally, an instrument was developed for measuring frictional forces of small magnitude ranging from below 0.01 dyne to about 50 dyne.[24] The apparatus was used extensively in friction studies of fine wire samples and of individual textile fibers under U.S. Department of Agriculture Grant No. 12-14-100-7661(72). The approach should be particularly valuable in studying the behavior of sliding contacts.

i) Machinability of Metals

Work under this task was not initiated due to the resignation of Dr. John A. Bailey to accept a position with North Carolina State University at Raleigh, North Carolina.

j) Solidification of Metals

In metal casting many of the important parameters of the process are dependent on the existing heat transfer rates and temperature gradients. Factors which govern heat transfer rates and temperatures, such as, interfacial energies and thermal properties of the casting and mold, also determine the mold life and solidification rates. It was the purpose of this task to obtain quantitative information on these factors for the solidification of metals cast into metal molds.

Two stages of the casting process can be identified. In the first stage, liquid metal is in contact with the mold and high mold temperatures and high heat transfer rates are obtained. It is this first stage which is of primary interest with respect to mold life and with the initial formation of the surface of the casting. In the second stage, a significant amount of casting has formed and an "air gap" exists between the casting and the mold. This stage is of importance in governing overall solidification rates.

In this task the first stage was studied for the initial solidification of lead-tin alloys on steel. In order to measure the thermal response and heat transfer rates, transient temperatures in the steel plate were measured when the liquid alloy was poured onto the plate and when the plate was submerged into a liquid bath. Second stage measurements were concentrated on the time for the "air gap" formation. Two methods were used. An electrical contact method was simpler and appeared to give a more positive indication; however, an ultrasonic pulse echo method proved to be feasible also.

Further work beyond these preliminary studies was discontinued as the task leader was transferred to another unit of Georgia Tech.

k) Gas-Solid Interactions

Initial efforts under this task involved the construction and calibration of a high precision adsorption apparatus for a broad range of gas-solid interaction studies. In addition, a conventional volumetric system to study multilayer formation and a gravimetric system to study two-dimensional phase transitions were constructed. Measurements of the interaction of neon, argon, krypton and xenon with boron nitride were made using the high precision apparatus.[25]

During the remainder of the program a statistical thermodynamical treatment for heterogeneous surfaces was developed, and studies were made of monolayer and high coverage adsorption of krypton on graphite, and monolayer coverage of krypton on (1,1,1) copper.[26,27]

The subject of physical adsorption was extensively reviewed by Pierotti and Thomas.[28] Pierotti also published discussions on the virial expansion treatment in physical adsorption[29] and on second and third order interactions of benzene with graphite.[30]

1) Surface and Diffusion Coatings

In the first year of this task a literature survey and a preliminary survey of the defense or space oriented industry in the specific area of high temperature, oxidation resistant surface and diffusion coatings were made.[31] These surveys were conducted to identify technology gaps and to determine research needs.

The literature survey was conducted by a search of the abstracts found in Chemical Abstracts, STAR, and the abstract files of the High Temperature Materials Division of the Engineering Experiment Station of Georgia Tech. Key papers, summaries, and reports were read beginning with the year 1963. The survey of private and government facilities involved with high temperature, oxidation resistant coatings was accomplished by means of a questionaire.

Analysis of the surveys resulted in research recommendations in the categories of new coating and/or new coating concepts, deposition techniques, basic data, and evaluation methods. One specific recommendation was that the coating process, chemical vapor deposition (CVD), be studied from a basic engineering approach. Knowledge of this process would also further the understanding of many other industrial coating processes, such as pack cementation, in which CVD is the primary coating mechanism.

Initial experimental CVD studies were made of the hydrogen reduction of silicon tetrachloride to produce a solid silicon coating on a tungsten wire followed by a detailed parametric study of the process. The parameters included wire temperature, hydrogen flow rate, silicon tetrachloride partial pressure, and total stream pressure.[32]

3. Scientific Significance

Individually each task under the program has made a contribution to the fundamental knowledge of surfaces or interfaces. However, the real significance of the research is the collective nature of the knowledge generated. By the multi-task, multi-discipline approach it should now be feasible to tackle, within the Institute, significant practical problems related to interface phenomena in engineering materials.

Project THEMIS had two basic objectives: the strengthening of the graduate program at the institution and the generation of basic knowledge for solving future defense problems. The participation of faculty and students from several schools and divisions, the development of specialized laboratories in these units, the publication of papers and theses, and the stimulation of cooperative research were accomplishments towards the first objective. The focussing of basic knowledge on defense problems was difficult because of the lack of a formal mechanism for coupling with federal laboratories. It is suggested that in the future consideration be given to assigning direct responsibility to appropriate laboratories for achieving the required coupling with universities.

It is also of significance to note that during the course of the program two major professional meetings were attracted to the campus, the 45th National Colloid Symposium of the Division of Colloid and Surface Chemistry, American Chemical Society, in 1971 and the Symposium on Field Ion Microscopy in Physical Metallurgy and Corrosion in 1968. And in 1972 a new interdepartmental Masters program in Surface Science and Technology involving members of the THEMIS team was initiated.

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III. SCIENTIFIC REPORTS AND PAPERS

The following scientific reports or papers are anticipated for publication:

J.R. Stevenson, H.W. Ellis and R.J. Bartlett, "Reflectivity of $Cd_x Zn_{3-x} As_2$ Semiconductor Alloy Systems," in Conference Digest, 3rd International Conference on Vacuum Ultraviolet Physics, held in Tokyo, Japan (1971).

J.R. Stevenson, H.W. Ellis and R.J. Bartlett, "Vacuum Ultraviolet Spectroscopy of Solids Using Synchrotron Radiation with Auger Spectroscopy for Analysis of Sample Surface Contamination," to be published.

R.N. Ramsey, H.E. Thomas and R.A. Pierotti, "Modification of a Precision Adsorption Apparatus. The Interaction of Gases with Boron Nitride," to be published in J. of Phys. Chem. 76 (1972).

B.R. Livesay and E.A. Starke, Jr., "Interaction of Dislocations with Interfaces," accepted for publication by Acta Metallurgica.

B.R. Livesay, "Micro-tensile Instrumentation," to be submitted to Rev.Sci. Instruments.

In addition, publications are expected to result from the Ph.D. theses of J.L. Carden and J.D. Phillips.

IV. PROFESSIONAL PERSONNEL

The following professional personnel participated in the research under Project THEMIS:

Edwin J. Scheibner, Research Professor of Physics, Program Manager

Waldemar T. Ziegler, Regents Professor of Chemical Engineering

Charles W. Gorton, Professor of Chemical Engineering

Robert F. Hochman, Professor of Chemical Engineering (Metallurgy)

Robert A. Pierotti, Professor of Chemistry

James R. Stevenson, Professor of Physics

Raymond K. Hart, Principal Research Scientist

John A. Bailey, Associate Professor of Mechanical Engineering

John A. Murphy, Associate Professor of Mechanical Engineering

Edgar A. Starke, Jr., Associate Professor of Chemical Engineering (Metallurgy)

Helen E. Grenga, Assistant Professor of Chemical Engineering (Metallurgy)

James M. Bradford, Assistant Professor of Mechanical Engineering

L. Neal Tharp, Senior Research Scientist

Mathew E. Sikorski, Senior Research Scientist

Billy R. Livesay, Research Scientist

Gary W. Simmons, Research Chemist

Roger P. Woodward, Research Engineer

Jan C. Eriksson, Post-Doctoral Fellow

V. DISSERTATIONS

The following dissertations resulted from full or partial support by Project THEMIS:

"Interaction of Inert Gases with Hexagonal Boron Nitride," Reginald Ramsey, Ph.D. (Chemistry), Winter Quarter 1970.

"The Determination of Microstrains and Antiphase Domain Size Produced During Ordering of a NiMo Single Crystal," Fu-Wen Ling, Ph.D. (Chemical Engineering), Winter Quarter 1971.

"Field-Ion Microscope Studies of Fine-Structures in Steels," B.N. Ranganathan, Ph.D. (Chemical Engineering), Winter Quarter 1972.

"Model Studies of Vacuum Sintering Treated as a Creep Process," Ronald W. Umphrey, Ph.D. (Mechanical Engineering), Winter Quarter 1972.

"A Detailed Study of Submonolayer and Multilayer Adsorption of Krypton on Graphite," David Newsome, Ph.D. (Chemistry), Winter Quarter 1972.

"The Interaction of Non-Spherical Molecules With Homogeneous Surfaces," Joseph Delay, Ph.D. (Chemistry), Spring Quarter 1972.

"The Adsorption of Krypton on the (1,1,1)Face of Copper," John L. Carden, Jr., Ph.D. (Chemistry), Spring Quarter 1972.

"L-Shell Auger Intensities and Energies for 3-d Transition Metals," J.D. Phillips, Ph.D. (Physics), Fall Quarter 1972.

"Auger Spectroscopy for the Study of Surface Contamination in Semiconductor Devices," R.P. Woodward, Ph.D. (Electrical Engineering), Fall Quarter 1972.

"Optical Properties of the Semiconductor Alloy System Cadmium Zinc Arsenite," Maury Zivitz, Ph.D. (Physics), Winter Quarter 1973.

"Optical Properties of Semiconductor Alloy Systems by Auger Spectroscopy and Optical Reflectivity," Harry W. Ellis, Ph.D. (Physics) Spring Quarter 1973.

"Field-Ion Microscope Studies on Surface Properties of Titanium Alloys," R. Kuman, Ph.D. (Chemical Engineering), Spring Quarter 1973.

"Reacting Flow in Porous Media," Alan C. Merritt, Ph.D. (Chemical Engineering), Spring Quarter 1973.

VI. INTERACTION WITH INDIVIDUALS OR ORGANIZATIONS

Members of our research group have interacted with numerous individuals and organizations through visits, scientific meetings, consultations and other sponsored programs. Some of these are tabulated below.

Individuals

Dr. L.H. Jenkins, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Dr. W. Pillinger, Savannah River Laboratory, Aiken, South Carolina

Dr. T.W. Haas, Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio

J.M. Blasingame, Avionics Branch, Wright-Patterson Air Force Base, Ohio

Dr. J.O. Porteus, Naval Weapons Center, China Lake, California

Dr. John J. Burke, U.S. Army Materials and Mechanics Research Center, Watertown, Mass.

Dr. Fred Leonard, U.S. Army Medical Biomechanical Research Laboratory, Walter Reed Army Medical Center, Washington, D.C.

Institutions

U.S. Naval Research Laboratory, Metallurgy Branch and Semiconductor Branch

NASA Marshall Space Flight Center, Huntsville, Alabama (Astrionics and Materials)

Lehigh University, Bethlehem, Pa.

N.C. State University, Raleigh, North Carolina

Ohio State University, Columbus, Ohio

Batelle Memorial Institute, Columbus, Ohio

Westinghouse Research Laboratories, Pittsburgh, Pa.

Varian Associates, Palo Alto, California

Bell Telephone Laboratories, Murray Hill, New Jersey

Meetings

45th National Colloid Symposium held at Georgia Tech in June 1971

Symposium on Field Ion Microscopy in Physical Metallurgy and Corrosion held at Georgia Tech in May 1968

Member of staff attended the Tri-Service Meeting on Corrosion of Military Equipment at Annapolis, Maryland, November 19-20, 1969

Dr. E. J. Scheibner presented a series of invited lectures on "Inelastic Scattering of Low Energy Electrons" at the NATO International Summer Course on Fundamental Processes on Semiconductor Surfaces held at the University of Ghent, Belgium, August 26--September 6, 1968

Other Sponsored Programs

ARPA Program on "Stress Corrosion Cracking" with Naval Research Laboratory, Lehigh University, Carnegie-Mellon University and the Boeing Company (Contract No. Nonr-991(15).

NASA Program on "Development of Microcircuits for Space Applications" (Contract No. NAS 8-25667).

AEC Program on "Surface Properties of Magnetic Materials" (Contract No. AT-(40-1)-2755)

VII. PATENTABLE INVENTIONS

There were no patentable inventions resulting from the sponsored research under this contract.

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13. ABSTRACT

The purpose of the research was to examine in a fundamental manner various phenomena occurring at interfaces between different materials, including the gas-solid interface, and their influence on the behavior of materials in engineering applications. A broad research program included fundamental surface science, e.g., adsorption and surface thermodynamics; the development of surface analytical techniques, e.g., Auger electron spectroscopy and micromechanical techniques; applications, e.g., friction and wear, and semiconductor process studies; and fabrication methods, e.g., chemical vapor deposition and sintering.

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